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A B S T R A C T

Open and decentralized technologies such as the Internet provide increasing opportunities to create knowledge and deliver computer-based decision support for multiple types of users across scales. However, environmental decision support systems/tools (henceforth EDSS) are often strongly science-driven and assuming single types of decision makers, and hence poorly suited for more decentralized and polycentric decision making contexts. In such contexts, EDSS need to be tailored to meet diverse user requirements to ensure that it provides useful (relevant), usable (intuitive), and exchangeable (institutionally unobstructed) information for decision support for different types of actors. To address these issues, we present a participatory framework for designing EDSS that emphasizes a more complete understanding of the decision making structures and iterative design of the user interface. We illustrate the application of the framework through a case study within the context of water-stressed upstream/downstream communities in Lima, Peru.

1. Introduction

1.1. Technological advances for decision support in environmental resources management

Developments in virtual technologies for data collection, processing, transmission, and visualisation provide an increasing opportunity to create and exchange data, information, and knowledge for decision support in environmental management (Beven et al., 2012). For clarity and consistency this article first establishes the terminological differences: "In computational systems **data** are the coded invariances. In human discourse data are that which is stated, for instance, by informants in an empirical study. **Information** is related to meaning or human intention. In computational systems information is the contents of databases, the web, etc. In human discourse systems information is the meaning of statements as they are intended by the speaker/writer and understood/misunderstood by the listener/reader. **Knowledge** is embodied in humans as the capacity to understand, explain and negotiate concepts, actions and intentions (Zins, 2007)".

The Internet in particular, allows for an unprecedented level of information-integration, providing the possibility to combine new and existing data and technologies (interoperability) and cope with growing resources and number of users (scalability) through the adoption of distributed systems (cloud computing). This evolution facilitates access to existing scientific and official datasets, for instance through standards such as the Open Geospatial

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Consortium's, Sensor Model Language, Sensor Web Enablement and Sensor Observation Service (Vitolo et al., 2015). It has also promoted non-conventional data generation activities, such as crowdsourcing, social networks, online surveys, unofficial data repositories, and citizen-science monitoring (Buytaert et al., 2014; Georgiadou et al., 2011). These sources may provide complementary information resources, particularly for data-scarce areas. Although some of the information may be affected by a higher level of uncertainty, their uptake within decision making processes is well-aligned with the principles of post-normal science (Funtowicz et al., 1992).

The exponential growth of these information sources and related technologies has implications for the way in which they are leveraged by environmental decision support systems (EDSS) to support growing public and private decision-making needs. Here, we define EDSS as computer-aided environmental information systems that support unstructured and semi-structured decision-making in environmental management contexts (McIntosh et al., 2011). The anatomy of these decision support systems typically contains three components: (1) databases, (2) analytical processing algorithms (e.g. environmental models), and (3) a user interface. The latter allows users (i.e. the decision makers) to interact with the information but typically hides the technological complexities.

1.2. Environmental decision support systems in a polycentric governance context

The diversification of information sources and availability implies their democratisation for decision support across multiple governance actors and scales (Buytaert et al., 2016). The idea of information democratisation has gained particular significance as part of debates on re-positioning the role of science in society through transdisciplinary processes of engagement with science and stronger involvement of citizens (Scott and Gibbons, 2001; Nowotny, 2005). However, in reality, EDSS solutions continue to be strongly single-actor oriented and science-driven (first versus second generation “Environmental Virtual Observatories” in (Karpouzoglou et al., 2016a)). As such, they are more closely aligned with monocentric (centralised) and technocratic governance structures that are incompatible with high institutional and geographical diversity (Lankford and Hepworth, 2010). The availability and access to information (Ransbotham, 2015) and environmental decision support for the wider range of actors involved remain impeded by lack of understanding of institutional, cultural, and geographical differences. As a result, there is risk that environmental governance processes can become dominated by the better-educated or politically-connected. Political science scholarship highlights that the chances of a particular policy option being adopted in an environmental governance context may largely be determined by the extent to which powerful actors see that option as meeting their interests and/or values (Underdal, 2010).

This has implications for how we conceive of power relations in the context of monocentric and polycentric governance arrangements. The classic monocentric approach ultimately assumes highly centralised forms of power (often concentrated around the State). However, the polycentric governance model attempts to capture and describe a more distributed model of power which makes more explicit linkages with local actors, everyday resource management practices, informal institutions and indigenous knowledge systems (Pahl-Wostl, 2009; Lankford and Hepworth, 2010; Underdal, 2010; Boelens et al., 2015). A polycentric institutional arrangement has been defined as “a mosaic of nested subunits” of decision making rather than a fully integrated, hierarchical whole (Lankford and Hepworth, 2010). It recognizes a high degree of heterogeneity over a large geographic domain in the production and consumption of public goods (environmental resources) as well as policy preferences (Ostrom, 2009). Such a model is more supportive of bottom-up approaches to decision making that improves the voice of the public in matters that impact them directly (Arnstein, 1969; International Association for Public Participation, 2002; Irvin and Stansbury, 2004) and can ultimately enhance the ability to cope better with change and uncertainty (Ostrom et al., 1961; Huitema et al., 2009; Huntjens et al., 2012).

The polycentric model has gained significance in adaptive governance scholarship, for example, as part of addressing more explicitly the interaction between actors operating at different levels of governance but who may have different and overlapping spheres of responsibility in terms of policy and management (Folke et al., 2005). Adaptive governance brings emphasis on integrating ecosystem dynamics with management structures, fostering experimentation in policy design as well as anticipating surprise as a tool for learning (Gunderson et al, 1999; Karpouzoglou et al., 2016b). In the discussion of polycentricity and adaptive governance, the links with information management are still less well developed as compared to the understanding of institutional interaction (Lebel et al., 2006; Buytaert et al., 2016). In this article we therefore propose polycentricity as a useful concept for strengthening the understanding of both data and institutional diversity and how this understanding may inform a new approach to EDSS (Table 1).

Table 1
Types of knowledge and areas of knowledge with high potential for decision support, adapted from (International Institute for Environment and Development, 2014).

Type of knowledge	Description	Example	EDSS potential	Target users
Tacit knowledge	Knowledge that the knowledge holder is not aware of and is expressed through experience	Peer-peer exchanges; radio; tv; mobile messaging (text, voice, multimedia)	High potential (but underutilised despite opportunities to address local scale management goals)	Small scale or subsistence farmers, pastoralists, governmental officers, NGO workers
Indigenous, traditional knowledge	Local knowledge unique to a culture or society that is passed down in communities	Oral community histories	Intermediate potential (but difficult to operationalise)	Communities of elders, village councils, community religious and spiritual leaders
Participatory, citizens science knowledge	Knowledge held by citizens based on their daily lives	Citizens perceptions of climate change impacts, citizen monitoring	High potential (some utilisation but orientated towards scientific data harvesting)	Small scale farmers, agro-pastoralists, citizen science volunteers
Project/ programme knowledge	Generated from implementation of a programme or development project	Project briefings; online databases	High potential (some utilisation, easier to codify and integrate?)	Development programme administrators; international donors; NGOs, politicians, bureaucrats
Research knowledge	Acquired through scientific investigation	Empirical data; published literature;	High potential (over utilised but little spread outside scientific communities)	Scientists; scientific knowledge brokers; Policy makers

1.3. Tailoring EDSS: insights from human-computer interaction research

Developing EDSS for organisations is a well-recognized problem that is not unique to the environmental management application context (McIntosh et al., 2011). Many development projects are either cancelled before completion or unsuccessful (Díez and McIntosh, 2009). Research continues to find ways to improve EDSS solutions and in meeting user requirements, early participatory engagement and the use of prototyping is found to be a recurring theme across more successful approaches (Díez and McIntosh, 2009; Sieber et al., 2013). Yet a focus on task-based usability may not reveal what motivates and demotivates users from EDSS use (Cooper et al., Cronin); furthermore, the EDSS 'clients' are often specific groups of users without consideration of their potential links with other information providers and beneficiaries in a larger network of actors (i.e. polycentric decision making). Hence there is scope for bridging the gap between a well-developed tradition of co-design of software (Sieber et al., 2013) with participatory environmental management (Reed, 2008).

Although technologies evolve and become obsolete, the psychological basis behind successful human-computer interactions (HCI) in past products remains relevant in guiding the design of future technologies (Grudin, 2011). Among the guiding principles are cognition, perceptions, mental models, attention and memory (Ebert et al., 2012; Schnall et al., 2012; Wickens et al., 2004) - and customization. As to the latter, a design has to be sensitive to the users' preferences, the environments they operate in, and their value systems (Callahan, 2005; Stone et al., 2006; Ishak et al., 2012; Shin, 2015; Alostath et al., 2011). HCI design prioritizes how individuals and cultures interpret, understand and respond to different tools (e.g. software, new information, or methods), build relations and define context for using these tools, and how they are exposed to different information resources, and share resources and information (Sedlmair et al., 2012). It also seeks to prevent information overload, for example through embedded computation and interactive information retrieval that is adaptive to personal learning strategies (Ebert et al., 2012; Ruthven, 2008). It is thus linked to research areas such as scientific visualisation, data mining, and information design, which push the envelope of what can be communicated with data, and in doing so, open new opportunities for extending their outreach and impact for non-technical audiences (Grainger et al., 2016; Karpouzoglou et al., 2016a; Ebert et al., 2012; Spiegelhalter et al., 2011; Vitos et al., 2013; Zooniverse, 2015).

HCI design seeks initially to build usable products, but increasingly a good user experience needs to be taken into account for the product creation to be justified and its use to be sustainable [User eXperience (UX) design (Kuniavsky, 2010). The premise is that a usable product is not necessarily a valuable product and the user's definition of what constitutes good experience needs to be the starting point. As a concept, there is no clear scientific consensus yet of what constitutes a good user experience as experience is by definition intangible, subjective, and contextual; however as a method, there is a clear aim to design the experience before the product (Law et al., 2014; Lallemand et al., 2015). The UX design method draws heavily on formative user research and user interactions with early, low-fidelity prototypes of the technology for creative inspirations using a rich and evolving design toolkit (IDEO.org, 2015). Although the method has been well tested in commercial products e.g. groceries shopping websites, banking facilities, design of TV apps, tablet operating systems, and smart mobile phones, we identify a broader potential for its application in defining and crystallising in an iterative, participatory way, the elements that constitute useful (relevant), usable (intuitive), and exchangeable (institutionally unobstructed) information for decision support for different types of actors within a polycentric governance arrangement.

In this paper we describe our new user-driven approach, which departs from standard software application design models such as Waterfall (Royce, 1987) and Agile (Martin, 2003) in the diversity of users, sources of environmental information and knowledge, decision-making analysis, and forms of EDSS tools considered. We begin by proposing the design criteria (section 2.1) for polycentric decision support system development, and follow with an elaboration of the methodology in two parts. First, we describe an active field-based discovery phase to elicit a better picture of decision-making structures and processes and existing experiences with access to information (Section 2.2). Second, we set out a participatory design phase of the decision support system that leverages the interdisciplinary nature of the research team through rapid prototyping and testing (Section 2.3). We illustrate the method (section 3) through a case study within the context of upstream/downstream water users in Lima, Peru, who are adapting to water scarcity at the community as well as at the regional decision making scale. As such, the case provides an excellent test-bed for developing a participatory design experiment for evaluating how EDSS could be designed to map onto existing multi-actor interaction and promote the creation and exchange of useful, useable information at and across different scales. In the final section, we critically reflect upon the merits and limitations of the approach.

2. A user-driven design methodology

2.1. The design criteria for polycentric decision support

The overall methodology consists of an iterative research and design process with the objective of defining and differentiating the user requirements for EDSS. User requirements in a polycentric governance context can vary widely based on the range of actors (decision makers) identified and require a participatory approach whereby scientists, technology designers, and the actors themselves are collaborating in all phases of refinement. A pre-existence of strong partnerships and allowance for relationships with actors to form over a longer period of time (much prior to the design exercise taking place) form favourable conditions for ensuring broad participation of actors.

The design criteria along three dimensions, i.e. usefulness, usability and exchangeability, underpin the user requirements of information for decision support for each type of actor (see also Fig. 1):

- **Useful information:** information and interaction meets decision making goals of actors within their respective roles and interests.
- **Usable information:** information and interaction is intuitive and can be implemented by actors given their level of information and technological literacy.
- **Exchangeable information:** information flow and interaction is unobstructed by institutional and infrastructural barriers.

These can also be understood as the criteria for EDSS designs that generate actionable knowledge (Karpouzoglou et al., 2016a; Lemos, 2015; Shotter, 2004). Useful and usable information are familiar concepts in science and technology design domains (McIntosh et al., 2011; Nielsen, 2015; Eden, 2011; Liu et al., 2008; Campos and Nunes, 2007). In environmental decision making contexts, useful information can be thought in terms of how information can feed into specific goals relating to environmental decision making. Usefulness is to some extent subjectively defined

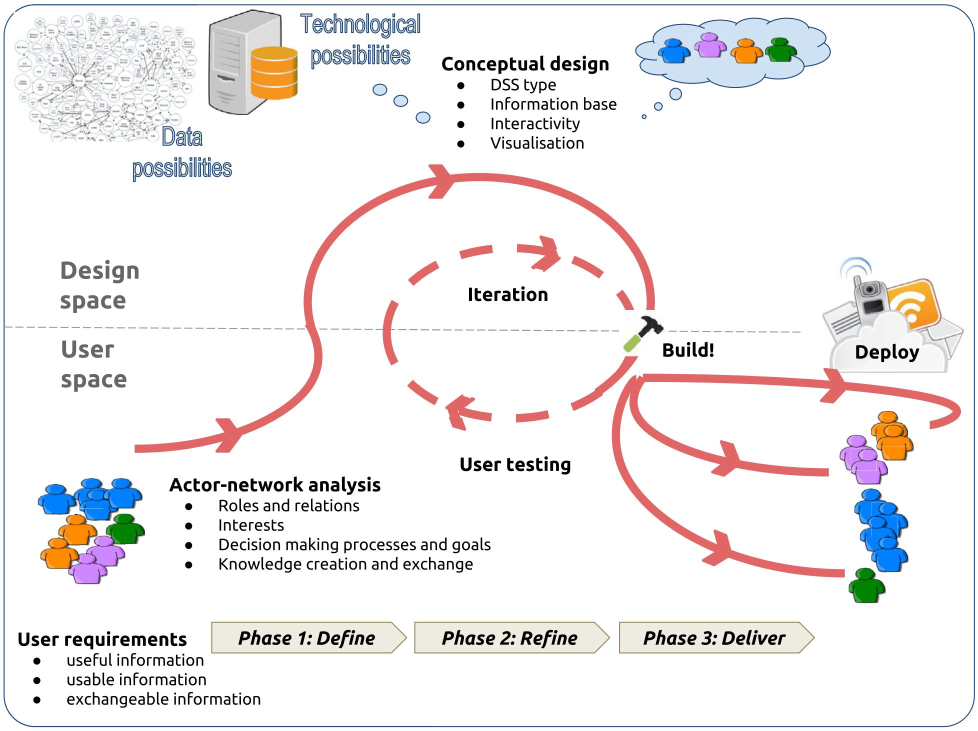


Fig. 1. EDSS design methodology for polycentric management support. It is a process that is framed by the development of the user requirements/specifications i.e. definitions and differentiation of useful, usable, and exchangeable information for the different types of actors and scales within a polycentric network. The process occurs between highly interactive user and design spaces. It begins with an identification of the actors and an analysis of their decision-making practices in the user space (phase 1) and the development of user personas based on this analysis to aid design tailoring in the design space. Single or multiple iterations of conceptual design can take place before the EDSS is adequately tailored for different users (phase 2), at which point technical development (phase 3) can begin.

[see review 28], and in a polycentric model where the interests and roles of the actors and nature, scale, and priorities of decision making are diverse, perceptions and therefore the definition of useful information with respect to pre-existing knowledge can be expected to be heterogenous. Given a common pool of environmental resources and potentially conflicting interests, some overlaps may exist, but even in this case, the domain of interest in time and in space is likely to vary accordingly to the decision-making scales. A local farmer may only be directly interested in new information related to their immediate vicinity, whereas a policy maker may require a more regional perspective. Information that is only remotely useful may be perceived as noise and render the EDSS suboptimal.

Usable information, on the other hand, relates more to intuitive design and the ability for users to cognitively seize and process information being presented for translation into new knowledge (Jörn Luciënneet al). Web-based forms of EDSS are optimal for a higher degree of information integration and interactivity, but may only be appropriate with computer literate users. Likewise, scientists and science-literate users are accustomed to information exchange in the form of highly complex multidimensional figures or highly condensed numbers (indicators, signatures), as these maximize the amount of information that can be delivered in a single instance. For the lay-person who is untrained, these forms of information may be overwhelming and could be easily misinterpreted. In many instances, the users may be illiterate (Huenerfauth, 2002). Similarly, scientists and highly science-literate decision makers who are used to condensed forms of information may find video-graphical forms of knowledge tedious.

Unlike useful and usable information, exchangeable information is a criteria that is particular to the case of polycentric decision making and relates to the connectedness between different types of actors. In reality, data, information, and knowledge are owned by different institutions with different level of openness to sharing. This forms significant institutional barriers that continue to exist even within the same type of actors in both cases of complementary and conflicting interests. Furthermore, even in an ideal world where information is truly open, information can still be obstructed due to infrastructural barriers such as a lack of digital access, particularly so in remote areas and affecting actors at local scales who are the most vulnerable under environmental pressures. The design of EDSS needs to be sensitive to these limitations which will vary for the different types of actors, and seek out new ways of linking the actors and the information/knowledge they own/produce.

2.2. Phase 1: actor and decision-making analysis

Prior to any user-driven design to take place, knowledge of the users and their decision-making needs is paramount. Thus the first phase of the method is a critical one that aims to identify key actors in relation to the environmental resource of concern (Reed et al., 2009) and the decision-making institutions and practices they are involved in. It is conducted through contextual study, i.e. an immersive field-based study of possible users in the context of their decision making roles and activities (where they work) based on qualitative enquiry. The alternative is a desktop analysis but the nature of polycentric governance/decision making is that it occurs across landscapes and across social networks and thus require a more emphatic approach to build understanding of user realities. The analysis is best performed by a local actor(s) embedded within the social network to minimize external biases and second hand knowledge. The objectives are thus (1) to identify important actors (roles) given an environmental resource at stake; (2) their rights, responsibilities, and interests over the environmental resource as well as knowledge and information that they own, produce, and/or identify as a need; (3) their relationships between each other, which could be over complementary or conflicting interests (Reed et al., 2009).

Gathering user requirements can be done using various techniques ranging from simple brainstorming to surveys/questionnaires, interviews, focus group discussion sessions and so on. Due to the dynamic and fluid nature of roles in environmental decision making, a combination of techniques rather than a single technique is used to allow active and passive participation of the actors being studied. In particular, we rely on observations, interviews, focus group discussions, and social network mapping. The chosen approach partly stems from expertise and prior experience of the team members in participatory rural appraisal techniques.

A gap analysis is subsequently performed over the existing use and flows of information in the decision making process, to generate ideas of potential new ways for EDSS support. This allows the user requirements to be established, but requires multiple consultation between the design team (consisting of engineering scientists, social scientists, and technology designers) and a field team (who undertakes the stakeholder interactions and analysis) to build an increasing understanding of the users and their realities. This is a challenging phase for the team to resolve the different perspectives, experiences, and expertise of the team members in accurately understanding and representing the user needs. For some actors, specifically among the technocrats, these preliminary user requirements may be simpler and more easily concretized than those of the others. Yet the advantage of multiple iterations of dialogue between the design team and the field team as well as between the field team and the users is an ultimate result that is based on collaborative reflection and comprehension. A promising participatory technique that may be explored is cognitive mapping, which is a mind mapping technique that enables users to visualize their decision making processes and considerations with researchers facilitating (Elsawah et al., 2015). This particular method was not tested in the case study due to time limitations.

2.3. Phase 2: iterative design

In the second main phase, the user requirements are translated into design in the “design space”. As work during the stages in this phase involves a professional designer, the materials and tools used and described, as well as the consequent effects on design, may be representative of the designer's experience and preferences. It is important to stress that there are many design tools that can be used to achieve the same objectives and the UX design methodology is not prescriptive in the set of tools to be used; rather it requires flexibility of the designer to understand and respond to complex user requirements.

2.3.1. Conceptual design

Inspired by data and technological possibilities, but driven by knowledge of the users, the first range of ideas of EDSS concepts/tools are produced in a series of ideation (or brainstorming) sessions. Various media for decision support can be considered that include posters and fliers, in-person training sessions, video tutorials, and building applications (for both desktops and mobile devices).

The ideation process is driven by the development of user personas. Personas are a set of profiles formalized from the different actors identified in the “user space”. They are archetypes, but deeply grounded in the actors encountered in the field analysis (i.e. previous phase 1 of the methodology). They are meant to encompass descriptions of the user demographics and 'experiences', for example, their typical day-to-day activity, decision making goals, and existing practices in the use and exchange of information (Hanington and Martin, 2012), see also an example in Fig. 2a]. Persona use is important as they compel designers to focus their design practice on real people as opposed to abstract categories, and works as a filter to scientists' biases. The personas also facilitate more engaged interaction and discussion between members of the design team, and provide a human dimension of the users outside the user space. However, a disadvantage of their use is that it requires some form of melting of individual requirements into single profiles, and an alternative for a fully personalized design of EDSS is to analyse individual requirements (Sieber et al., 2013).

Ideation is further facilitated by the use of a technique called storyboarding (Fig. 2b). Storyboarding involves the production of a sequence of images that contain real life decision-making contexts for specific personas, their “touch points” (points of interaction at times of need) with EDSS, and early visual features of the user interface. The method forces the designers to think of the user's interaction with the EDSS in space-time context, and as such is particularly effective in the design of interactive tools (Buxton, 2007). It further allows a common understanding to be built within the design team and across the design and user spaces boundary. An advantage, which may also be the limitation, of the storyboarding activity is that it forces a distillation of complex user requirements into a select number of discrete solutions, which could result in some user requirements that are not fully addressed. An ideal approach is to continue to involve users at this stage through participatory design sessions, as this can help prioritise the ideas with the highest potential in terms of meeting user requirements, as well as provide an early exposure to the users to design technicalities.

2.3.2. Prototyping

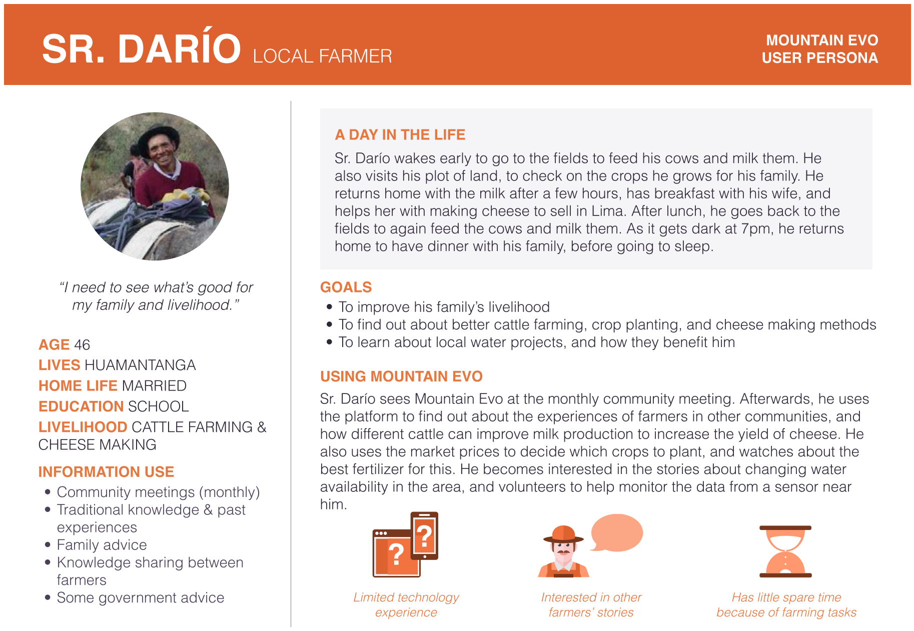
Drawing on the conceptual designs, wireframes (skeletal sketches, see example in Fig. 3) of the user interface and how the elements across these interact are subsequently produced. The wireframes are circulated around members of the field-research team before higher fidelity prototypes are built using prototyping software. Discussions at this stage can include clarifying scientific concepts and replacing scientific jargons with layman terminologies.

Subsequent to this, the prototypes are turned into more refined computer drawings. The focus of the design shifts to visualisation for the non technical audience. Multi-user considerations are made through parallel prototyping to cater to the range of usability requirements across the different personas, and the prototypes are presented as a part of a cohesive web application to facilitate evaluation with the user using a prototyping software.

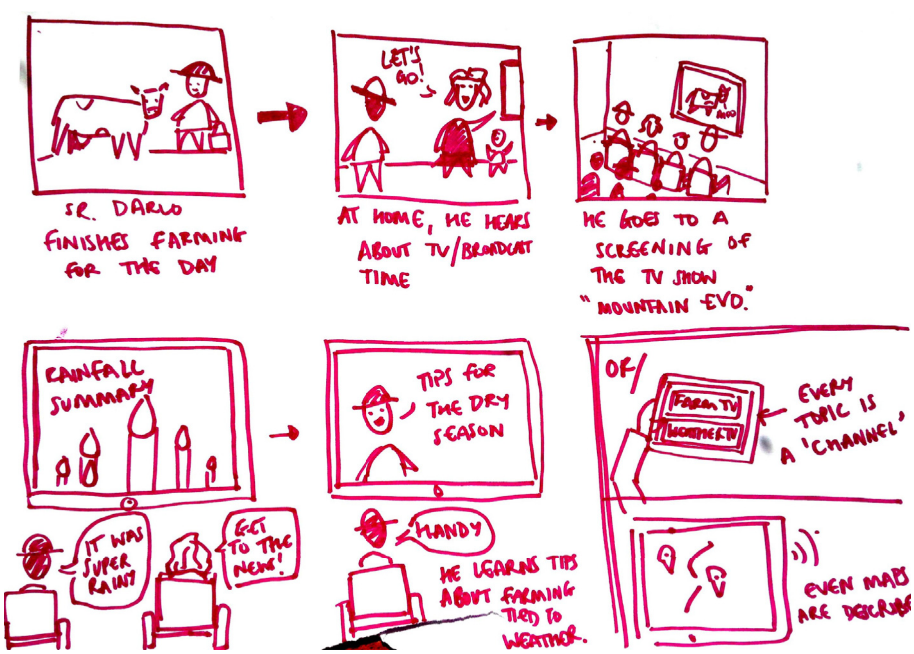
2.3.3. User testing and design iteration

In a critical phase of the method, the working prototype is fed back into the user research space for full user testing. One-on-one user testing sessions are rapidly conducted with a real life sample (5–10 individuals) representing the different user personas to observe and understand their interaction with the different prototypes, and elicit new design suggestions.

During the interaction, the users are asked to vocalise their thoughts (to 'think aloud') on the prototypes, while designers take a passive role of observing instead of aiding the interaction [for further details on the method see 63]. Some observation cues that may aid the generation of insights are presented in Fig. 4. Whenever possible, the testing/interview sessions were fully audio-recorded. However, some actors may be concerned about



(a)



(b)

Fig. 2. (a) Example of a user persona (Sr. Darío i.e. fictional farmer from Huamantanga) that contains descriptions of his demographics, typical day-to-day activity, decision making goals, and details related to existing information and technological use and exchange (b) Example of a storyboard to envision how Sr. Darío will interact with rainfall data from local community monitoring. The storyboarding method requires an explicit consideration of the purpose of EDSS in the user's context of time and space.

conditions of anonymity as a result of inexperience with the scientific process, in which case only handwritten notes are kept.

The nature of the testing session is fully explained to the users, i.e. the unfinished nature of the prototype and the fact that designs can completely be changed if they do not meet their needs and interest. This allows for an open communication between the design team and the users for constructive feedback. The users are also asked at the end to suggest new ideas and potential opportunities of other use and users of the EDSS tools.

Based on the participatory activity, an analysis of usefulness, usability, and exchangeability issues are constructed using a combination of qualitative and quantitative methods, for example using content analysis of the user testing session notes (which in principle is similar to the thematic analysis used in (Sieber et al., 2013)) and statistical analysis of questionnaire responses. Clear directions on usefulness and usability will emerge from the analysis to aid further design tailoring for the different types of actors.

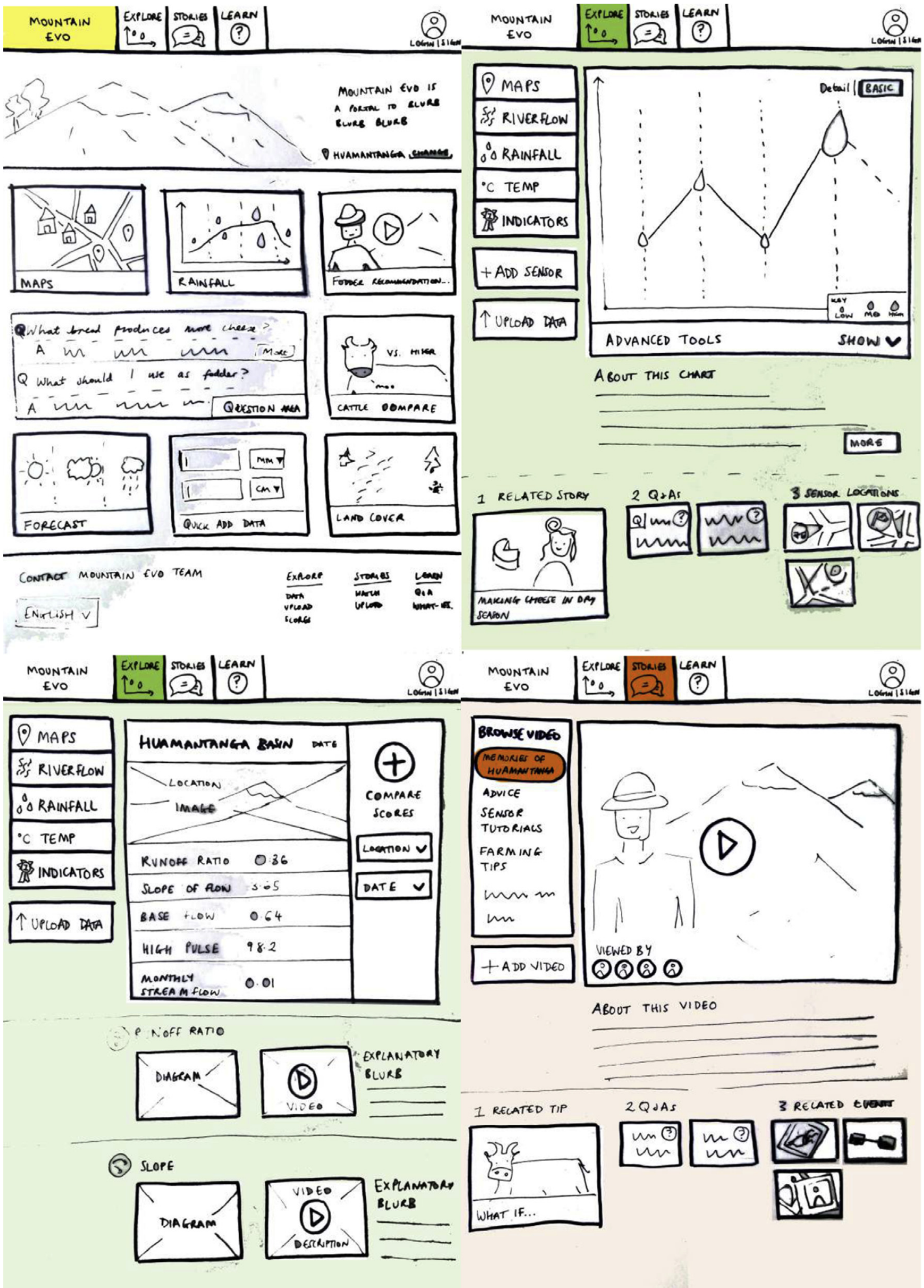


Fig. 3. Paper prototyping: development of wireframes to concretise ideas from conceptual design.

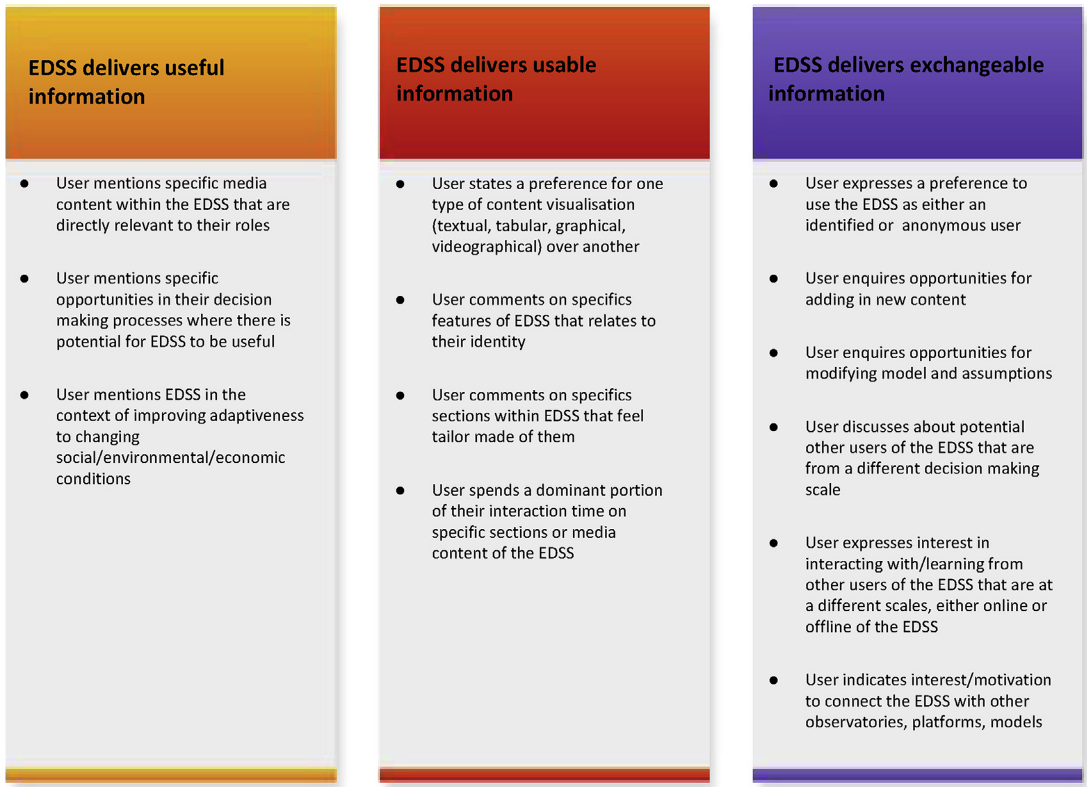


Fig. 4. Observation cues for gaining insights from user testing sessions.

3. Case study application: EDSS design in the context of high elevation remote social-ecological system

We present insights from an application of the design methodology in a case study of an upper Peruvian Andean agro-pastoralist region in the Chillon river basin, which is one of the three main basins (Chillón, Rímac and Lurín) providing water to Lima. The study was completed over the course of 6 months involving extended periods (1–2 weeks) of stay in the village of Huamantanga in the province of Canta, Lima.

3.1. Actor and decision making analysis

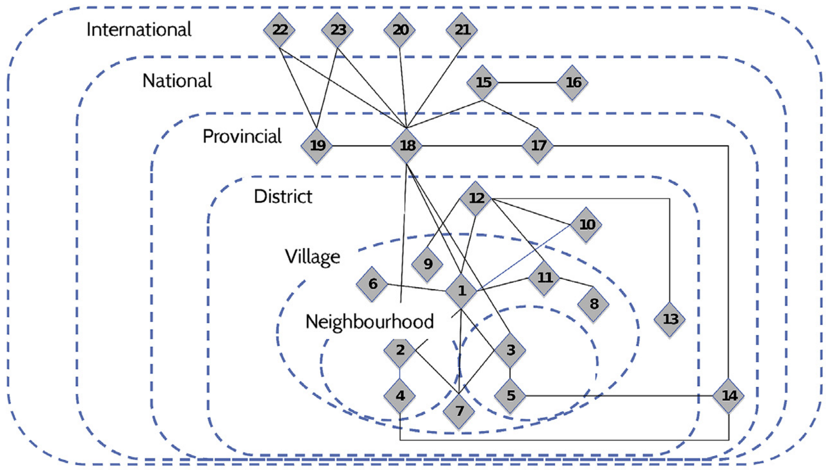
Reflections of the interactions resulted in a narrative of the multiple actors in relation to environmental resources management and conservation. Presently, data and knowledge regarding water resources are owned and produced by different entities. The actor-network diagram presented in Fig. 5 indicates an existing polycentric arrangement.

CONDESAN (a spanish acronym for the Consortium for the Sustainable Development of the Andean Ecoregion) is a transnational NGO aiming to generate scientific evidence to influence policy design that concerns Andean regions and communities (CONDESAN, 2010). To support their objectives, CONDESAN has played an important role in founding and coordinating a trans-Andean initiative for small scale participatory hydrological monitoring (Regional Initiative for Hydrological Monitoring of Andean Ecosystems, IMHEA in Spanish) and in providing expert advice to multiple governmental institutions in the participating countries (Celleri et al., 2010). In Peru, a recently introduced national law obliges the National Sanitation Services Superintendent (SUNASS in Spanish), a governmental institution responsible for drinking water regulation, to require all water companies under their purview to include investment in hydrological ecosystem services of catchments in their planning (Peru, 2013). Its decision making revolves around investing in existing and new conservation practices in the upstream, while the Environmental Ministry (MINAM in Spanish) is involved with the role of analysing strategies and experiences, and to support related efforts at the country level (Peru, 2013).

In this respect, the village of Huamantanga may provide an interesting perspective as a pilot experience for supporting such a mechanism using data-based evidence. Through the IMHEA initiative, CONDESAN began pairwise-catchment monitoring in the community in June 2014 to evaluate the impact of conservation practices in Huamantanga on water regulation in the upper catchment. This is complementary to traditional water and land management strategies already in practice within the community to improve water availability in response to an increasing experience of water scarcity.

The presence of local monitoring and regional to international interest in the data and knowledge generated and owned locally (scientific, indigenous) present many important questions, particularly around how local level actors, e.g. the farmers and their community level associations, may stand to benefit from similar types of information, in particular, in support of individual and collective decision making concerning optimal management of communal environmental resources. Irrigation water and land for grazing and cropping are becoming increasingly scarce due to changing climate conditions. As showcased by the different interests of actors (see also Table 2) water and pastoral land management decisions may be influenced by larger, more formal decision making structures beyond the local/community scale, that may impact and influence local environmental resource use.

The study of different actors is summarised in Table 2, which



No.	Actor
1	President of the community
2	Internal committee - Anduy neighbourhood
3	Internal committee - Shigual neighbourhood
4	Irrigation committee - Anduy neighbourhood
5	Irrigation committee - Shigual neighbourhood
6	Local Administrative Board of Water and Sanitation Service (Spanish acronym JASS)
7	Justice of the Peace: a Judicial Officer of a local court elected by the Community Magistrate's court
8	Parents Association for the School (Spanish acronym APAFA)
9	Comité de vaso de Leche: committee funded by a government program and in charge of preparing and providing breakfast to children under 6 years old
10	Gobernorship: the authority representing the president of the country and is in charge of monitoring governmental projects in the district.
11	School
12	District municipality
13	Health Post
14	ALA Chillón - Rimac - Lurin - Government water authority.
15	National Sanitation Services Superintendent (Spanish acronym SUNASS)
16	Peruvian Environmental Ministry (Spanish acronym MINAM)
17	Lima Water Company in charge of providing Potable Water and Sewerage Service of Lima (Spanish acronym SEDAPAL)
18	Consortium for Sustainable Development in the Andean Ecoregion (Spanish acronym CONDESAN)
19	Aquafondo: the water fund for Lima
20	Forest Trends
21	Imperial College London, Wageningen University (Mountain Environmental Virtual Observatory project)
22	Stanford University
23	The Natural Conservancy, international NGO

Fig. 5. Polycentric network of actors in land and water management in the Huamantanga, Lima case.

provides a preliminary synthesis of their user requirements with respect to decision support. In this case, the decision making scales of the actors also provide a natural basis of consolidation into user personas, which consist of 1) farmers and women in the community (represented by the persona 'Señor Darío' and 'Señora Rojas'), 2) NGO workers ('Gabriela'), 3) student and researchers ('Craig'), and 4) government-level policy makers ('Juan'). The persona profiles are provided in Supplementary Material A.

3.2. Iterative design

3.2.1. Conceptual design

The actor analysis resulted in highly diverse user requirements. A web-based (desktop and mobile) design developed quickly to integrate many of the design ideas. This was partly driven, and may have been biased by the designers' technical knowledge and experience in science-driven EDSS development, mobile apps in citizen science activities, and popular web services for content sharing and social networking such as Facebook and YouTube. Design activities thus focussed on the user interface of a web application, but with the idea that the design materials can be adapted accordingly for other types of uses.

Specific user requirements were translated into web tools (listed in Fig. 6) and organized into clusters: mapping and monitoring-based (data-driven) EDSS, model-driven EDSS, and uncodified knowledge exchange (communication- and knowledge-driven) EDSS following the classifications of (Power, 2002; Bhargava et al., 2007). The types of information considered included rainfall and runoff from local monitoring, digital terrain and land cover data from remote sensing, and local knowledge shared with field researchers over interviews during the field research. In the cases information does not already exist, dummies were used as placeholders.

During the storyboarding activity, storyboards were drawn in 5-min sprints for each of the EDSS tools and personas. For the policy maker Juan, NGO workers Gabriela, and student Craig, the interaction with EDSS were storyboarded with relative ease, as web-based tools are a natural part of their everyday tasks. In contrast,

Table 2
Analysis of actor interests, roles, decision making goals, and user requirements.

Scale	Actor	Interest/agenda/role	Decision making processes and goals	Useful information	Usable information	Exchanged(/-able) information
Local	Community members - farmers, women, youths (persona Señor Darío and Señora Rojas)	Adapting to environmental pressure by changing/diversifying livelihood strategies	How to manage environmental resources better to sustain or improve production from cattle farming; How to diversify livelihood strategies; How to benefit from and support local water initiatives (e.g. monitoring) being introduced by NGO; Occurs in monthly neighbourhood meetings (formal) and individually on a day-to-day basis	Cattle breed variety and care needs; Land and water availability for additional fodder production; Land and water requirements for different fodder varieties; Water efficient irrigation technologies; Cattle theft prevention; Other local experiences in economic activities such as cooperative production of cheese, handicraft sales, and eco-tourism	No prior exposure with scientific data visualisation: may require an assisted introduction; Spare time is limited due to field work: interaction time with EDSS should be minimal; Technology experience limited to TV, radio, mobile phones;	Traditional knowledge and historical experiences; Family advice and peer-to-peer exchange; Videos brought by visiting researchers; Occasional specialised training sessions from governmental advisors/ NGOs; Occasional presentations by visiting NGO actors
Intermediate, regional	NGO: e.g. IMHEA, CONDESAN (persona Gabriela)	Generating scientific evidence through monitoring at local scales to influence national level policy making; Supporting national level policy implementations at local scales; Fulfilling donors' interests	How to develop effective participatory monitoring programs to maximize opportunities of knowledge generation; How to improve engagement with local actors	Up-to-date access to monitoring data for quality control and analysis of impact of different land management practices; Socioeconomic information of participatory monitoring communities; Options for strategic planning of development activities in the region; Occurs periodically, also on the basis of interactions with related local, national and international actors	Raw and processed data formats	Monitoring data access is limited to regular (monthly) field visit; Knowledge is generated in-house; Regular dialogue occurs with national level actors; Periodical stakeholder interaction occurs with local actors
National	Governmental, semi-governmental institutions, e.g. SUNASS, MINAM (persona Juan)	Formulating and implementing national level policies	Optimal return on investment for payment of ecosystem services projects in the upstream catchments; Occurs as stipulated by new laws of payments of ecosystem	Evidence of conservation practices on water resources availability (economic); Progress on existing investment projects; New opportunities for investment	Succinct (highly processed) data format to inform immediately required decisions; Accustomed to scenarios and modelling output; Medium/high level of data literacy and computer proficiency	Knowledge from multiple sources integrated through in-house analysis; Consultants (private and NGOs) provide answers to specific questions
International	Scientists, e.g. Imperial College, MSc research students (persona Craig)	Providing scientific support and funding for local monitoring activities; Gathering data and local insights for scientific research	Generated new knowledge leveraging locally produced data and traditional knowledge	Monitoring data for research; Socioeconomic information of participatory monitoring communities ('case studies'); References and contacts	Raw data formats; High level of data literacy and computer proficiency	Interactions occur through intermediate actors (NGOs); Limited interactions with national level and local actors

it was more challenging to imagine how a desktop-based modelling tool would play out for Señor Darío, the farmer, in his everyday context particularly because his experience of knowledge access and sharing is primarily verbal and peer-to-peer, and his interaction with technology is limited, for example to TV, radio, and mobile phones. Additionally, game-based/role-play types of EDSS were initially considered but criticised by the field researcher to be perceived by Señor Darío as a waste of his time and a mockery of his livelihoods, and thus were not further pursued. Rather, the EDSS concepts in the farmers' storyboards recurringly translated into simpler visual design displays and involvement of a real person to mediate the information exchange. They are also supported by other types of more traditional channels of information communication technology such as TV and public screens.

3.2.2. Prototyping

The first tablet-based prototypes were subsequently produced using sketches and design and prototyping software. A design with the lowest usability threshold was always pursued to cater for the persona with no technical background, for example by designing for a touchscreen device (to work on a smartphone, tablet, or a public display screen), featuring content in tiles on the homepage in case users were unfamiliar with navigating tabs/menus, using icons to help explain diagrams, and using a consistent pattern across screens, for example with the tabs and other navigation options. As the user testing later revealed, these design decisions were mostly effective for a particular group of users i.e. those with the lowest technological literacy, whereas for some of the more experienced EDSS users, some features such as the icons were an unwelcome distraction.

Due to time and cost limitations and complicated travel logistics, the initial paper-based designs were not tested with potential users. Instead, the prototypes were tested with the field team and experts not linked to the research project for receiving external feedback. Minor suggestions to the designs were addressed while major questions were left to be answered during the user testing. For example, the term 'hydrological indicator' (scientific jargon) was changed to 'ecosystems services indicators' to relate to the

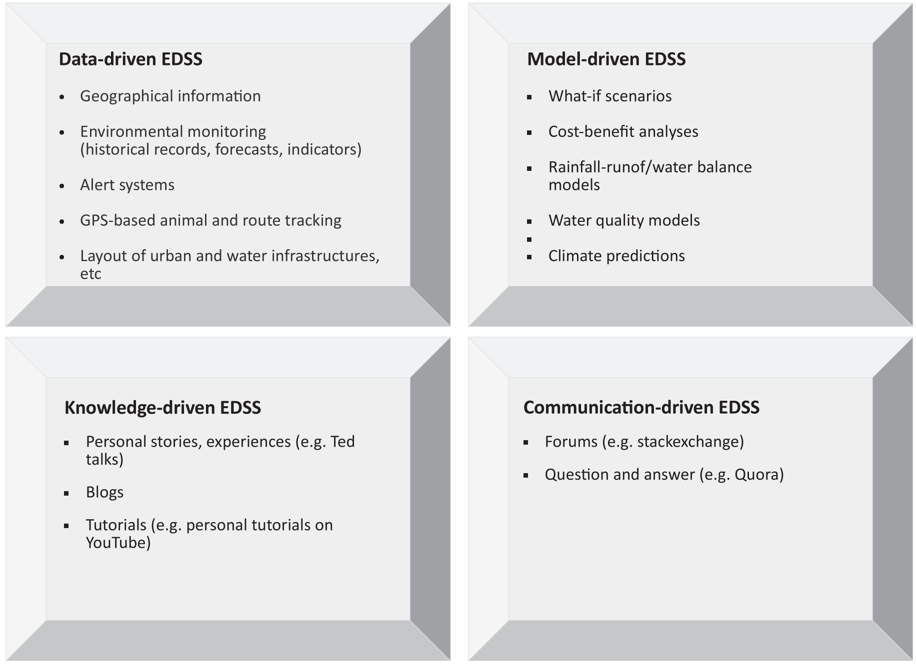


Fig. 6. Ideation of EDSS concepts based on scientific, technological and data possibilities.

(a) (b)

(c) (d)

Fig. 7. (a) Prototype testing with a local farmer (b) Prototype testing with a government official at the Ministry of Environment (c) Workshop with university students from a volunteering club Grupo de Alumnos Voluntarios de la Universidad Agraria de La Molina (d) Content analysis of user feedback on usefulness, usability, and exchangeability elements of the EDSS prototypes.

immediate interest of the policy makers.

The prototype delivered to the user space for testing consisted of the 4 clusters of the EDSS organized into tabs ('monitoring', 'stories', 'dialogue', and 'decisions', see also Fig. 7 and the interactive application at http://paramo.cc.ic.ac.uk/espa/EVO_v1/). The monitoring section consists of parallel visualisation of multiple environmental variables such as rainfall, river flow and temperature, in the standard scientific bar plots and line charts as well as icon-assisted time series visualisation. The stories and dialogue sections were allocated for exchange of knowledge such as personal

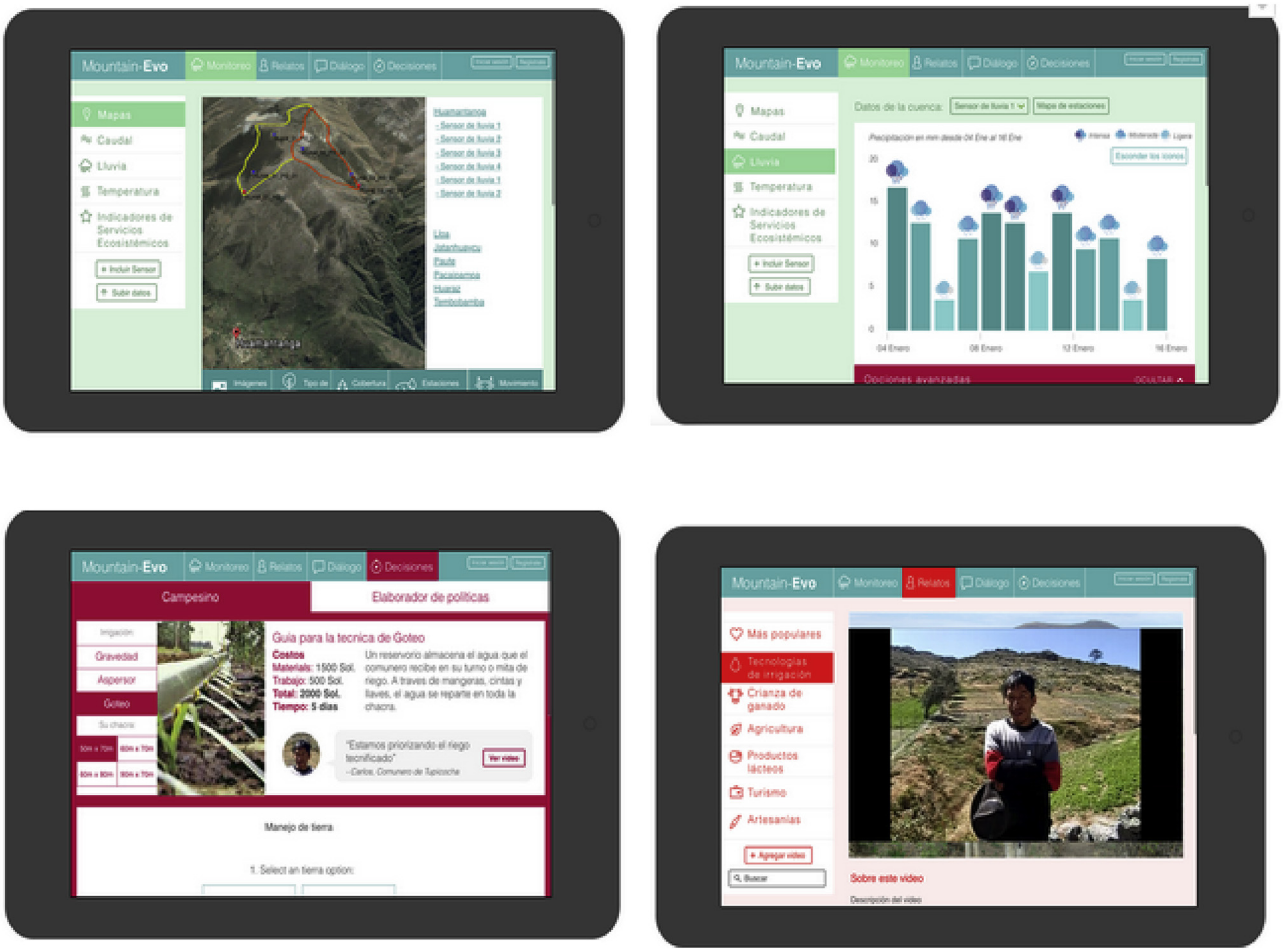


Fig. 8. The tablet-supported prototypes of the EDSS concepts (a) map (b) monitoring data (c) models (d) uncodified knowledge exchange. The interactive prototype is available at http://paramo.cc.ic.ac.uk/espa/EVO_v1/.

experiences and tutorials which tend to be in more amorphous forms. The decisions sections consisted of two designs of land and water management scenario-based tools catering differently for the locals and the policy makers.

3.2.3. User testing

The series of user testing was conducted with 6 farmers, 2 NGO workers from CONDESAN, and 7 policy makers (1 economist, 1 lawyer, 1 publicist, 1 agronomist and 1 engineer at SUNASS and 2 engineers at MINAM, Fig. 8). An exit questionnaire is administered at the end of the session (questionnaire, results and interpretations included as Supplementary Material B).

Farmers responded positively to the different graphics. For example, they were able to relate physical locations within their locality to points in a 2-D aerial image. One farmer commented: “this is the first time I see Huamantanga in this way” in response to a 3D imagery of their village. They were also able to interpret a 2-D map of vegetation cover from remote sensing data where the degree of vegetation coverage is only indicated by different gradients of colour. Notably, farmers were quicker to interpret the information contained in the rainfall hyetograph than the same information presented in a line graph. The variations in heights of the bars in the plots, aided by the gradients in intensity in the colour and rainyness of the accompanying icons of raining clouds proved to be intuitive. Likewise, the river flow hydrograph was found difficult to interpret, although this visualisation is the convention for hydrologists. In this way, we were able to refine the types of usable forms of information for these actors.

Furthermore, the farmers were also able to associate the information presented to their everyday activity. For example, a history of the previous 1–3 days of temperature data was deemed useful by them to identify trends towards frost conditions, whereas it was presumed by the designers that their requirement for useful information would be a model-driven forecast several months into the future. This reflects decision making practices by the farmers that is more short term rather than long term, as well as the appropriate types of environmental information that supports their experiential learning. Interest in learning how monitoring instruments work was indicated by attempts to access the related tutorials, which were dead-links in the prototype. Temperature was at the time of testing not monitored in Huamantanga, hence one farmer suggested the community can produce and access this data directly. This form of decision support tool was not conceived previously by the design team, and hence a purely user-driven and concrete pathway for information creation was identified through the activity.

The model-driven EDSS, on the other hand, proved to be unintuitive as predicted during the conceptual design, and proven as a roundabout way to answer their more direct, concrete questions regarding irrigation water management. Rather than scenario analysis, the “story” (video content sharing) and “dialogue” (question and answer) sections proved to be more real-life, direct way for them to access this information. This is also in line with their knowledge sharing practices outside of the virtual space, and explains their sustained interest in a video recording of a farmer from another Andean community. However, there were still limitations identified in communication through a screen, as a farmer stated: “This is nice but it is hard to translate from the screen to the field”. A SMS-service idea was also proposed in place of the online dialogue, but the farmers remarked that even though they use mobile phones, they do not use the texting facility. Based on these observations that farmers were able to receive and process information feeds but would find it challenging to have a 2-way interaction with any type of EDSS, all the designs evaluated require careful redesign particularly in the aspect of usability.

The observations with the farmer user group is a stark contrast to the user observations with the policy makers, where the monitoring data attracted general interest but indicated low level of usefulness, but the model-based EDSS attracted more interaction time and focus, especially for the wider river basin perspective. Suggestions were made to link the EDSS tool to data archives owned by specific national level governmental institutions to enrich the information pool. For these decision makers, it quickly became clear that the community perspective was not critical information for decision support. An exception was the publicist in SUNASS whose role was public relations, and for whom a social story behind the engineering and economics numbers is a valuable resource to support his specific role and decision making. In contrast, for the central actor of the polycentric network explored i.e. CONDESAN, the full portfolio were perceived to be useful, and particularly so the indicators summarizing catchment responses to various land conservation practices across all their monitoring stations. The users commented on the farmer bias in the portfolio of EDSS designs, nevertheless were encouraged by the possibility of supporting the use of such tools to disseminate monitoring data in a useable way to local communities.

Finally, the prototype enabled productive interactions with several surprise actors. Unplanned interaction with the NGO Network of Rural Agroindustry (REDAR acronym in Spanish), revealed new opportunities in their role to support an EDSS for the farmers, i.e. to participate in the virtual “dialogue” and respond to local needs. In turn, the EDSS was seen as a potential platform to showcase their activities, and generate evidence for existing and future funding. Similarly, brainstorming sessions with a group of volunteer students (Grupo de Alumnos Voluntarios de la Universidad Agraria de La Molina) interested in rural development was constructive. The students identified their potential role as moderators of the user forum and providers of technical support and capacity building for the farmers with the EDSS use and interpretation.

3.3. Implementation of a polycentric model based on insights from a user-driven design

Significant effort has been invested in the soft design aspects (i.e. user research and user interaction with prototypes in the early phase). This proved to be valuable for elucidating the diversity of the user requirements in a more collaborative way. This method also helped particularly so for clarifying the links between the information service and the user requirements across different decision-making scales.

Several design directions crystallized for the different actors. For the NGO CONDESAN, this comes in the form of a basin-wide tool for managing and communicating the results of the high altitude participatory monitoring activities and is primarily data-driven. For the policy makers and investors within SUNASS and MINAM, the same environmental analysis could be useful to enhance their basinwide perspective, but more elaborate information management and modelling facilities are required to fully support their decision making needs, which require a broader socioeconomic perspective and technical coordination with other government institutions for data sharing.

For the farmers in the upper Andes, conventional maps and specific forms of environmental time series visualisations (purely data-driven with very limited data processing), as well as local knowledge exchange in a video format revealed to be potentially beneficial EDSS tools. In consideration of limitations in infrastructure as well as users' lack of ability in using interactive tools, the display device will be community screens rather than personal computers or tablets. Other ideas that originated purely from the user testing sessions are also currently being implemented, for example, video tutorials for monitoring equipment and knowledge exchange through training workshops and inter-community visits. Since it is also in CONDESAN's long term interest to support this information exchange with Andean communities due to the long term interest in participatory monitoring, the NGO has assumed the responsibility to support this development financially and technically. Through participatory and iterative design, the redesigned EDSS will also have the benefit of better-tailoring.

Further discussions are ongoing regarding the role of REDAR as well as CONDESAN in supporting the operationalisation of the EDSS for the community of Huamantanga and similar communities in the upper Andes, as well as facilitating knowledge exchange between these communities offline. These again illustrate the usefulness of a method that aims towards capturing a wide range of users and scales to provide more creative solutions that maps onto existing relationships and experiences rather than a top down approach that may forcibly change how decision makers already access and use information.

4. Conclusions: merits and remaining challenges of a user-driven EDSS design approach

The goal of informational tools is to assist users in building their own knowledge base and guide their decisions (International Fund for Agricultural Development, 2011). We present a user-centred approach to EDSS design that allows the design criteria (user requirements) to be developed in a collaborative way with the users and remain part of an active research phase that lasts through the remaining chain of an information service design, from conceptual to detailed to final prototypes.

Through the use of parallel prototyping, the method allows technology to be introduced to a wider range of stakeholders. The users, as individuals and part of the community, filter the concepts for decision support based on their experience and expectations, while researchers take a step back from typical top-down roles that could be counterproductive. Participatory engagement across multiple actors (scientists, designers, policy makers, farmers) ensures that EDSS can be appropriately tailored. Our case study shows the potential benefits for farmers in remote areas, where access to environmental data is systematically hindered by data literacy and technological barriers. Here, despite the growth of environmental data in the public domain and from local monitoring, information flows are still primarily single-directional and new technology is still perceived to be the enemy of the poor. Our case study analysis also demonstrates that the user-centred design not only can improve the opportunities for the locals to benefit from the same pool of information, but also for downstream actors to access locally produced information and knowledge.

Furthermore, rapid prototyping with low fidelity products allows experimentation of the usefulness and usability of each form of data communication before any technical development is carried out. For this reason, valuable resources can be saved upfront. It provides a straw man proposal that allows discussion to take place by presenting a range of roughly formed ideas on the table to pave way for new, better ideas. This approach is particularly necessary in the context of actors in the lower scale of the polycentric network, who have no prior experience and access to conventional EDSS and for this reason require an introduction to the range of possibilities.

Lastly, the method requires that the users, scientists, technologists and designers look beyond their disciplinary and professional boundaries, and also reflect on their experience and tacit based learning. Observing the environment in which individual and collective decision-makers operate, collaboratively discovering what products or services brings value to them, and co-designing the user interaction with technologies in multiple iterations, could help avoid systemic pitfalls associated with the transfer and subsequent failure (as measured for example in terms of adoption rates amongst vulnerable and poorer communities) of "tested" fail-safe, low-risk and low-return technology packages. This has been identified to be a remaining challenge of real life applications of EDSS (McIntosh et al., 2011) and the methodology proposed here allows for learning through early mistakes. Furthermore, although the Internet can become a strategic tool for the flow of information, there are geographical regions where physical access is presently limited. A user-driven method allows this to be discovered first hand, and the mechanisms to remove infrastructural barriers or identify offline support need to be included as part of the deliberation process between actors with common interests.

Nevertheless, participatory approaches are time consuming and conditional on the build up of trust. While there can be no limits to the actors accessed in a polycentric network, in reality this is a more challenging task. Rapport and respect for opportunity costs are preconditions for the process to be successful (Hoffmann et al., 2007; Sedlmair et al., 2012), and the case in Lima showed how the stakeholder engagement is conducted through established working relationships. The human-centredness and time-intensive nature of the method also subjects it to sampling inadequacy, bias and unmet expectations when they are poorly managed. In addition, careful attention has to be paid to the power dynamics between the researchers and participants. This study was a case where the activity of environmental data collection existed beforehand, as the result of a local dynamic involving the Huamantanga community and CONDESAN without external scientific involvement. The decision for monitoring was therefore a result of a strong locally-rooted understanding of ecosystem degradation and its direct impacts on local livelihoods. Yet CONDESAN, as the broker, also brings their own expectations and priorities in terms of information design. Here, their motivations for information design were to bring in a poverty alleviation and social perspective, in a regulation of investment in watersheds, that has in principle more "utilitarian" origin of bringing more and better water to Lima. CONDESAN tries to level the playing field where players with clearly very different power meets. A design methodology that eventually directly engages with the different actors is nonetheless effective for minimizing or eliminating any biases of the broker. Furthermore, the transient nature of participatory projects makes it necessary to identify local actors that can play the role of a "champion" (van Delden et al., 2011) as well as advocate the participation and use of EDSS amongst the more marginalized groups. In the case study, this role was played by CONDESAN who was rather an intermediary actor. Finally, the greater diversity in solutions to EDSS implies reliance on a greater diversity of actors and informal relationships, which because of their fluid nature, may inevitably break. This remains a challenge in the long term and much harder thinking is required to formalize support and build in redundancies where the risk is greatest.

Our experiments show that a methodology that supports design that is conscious of the polycentric network is crucial for optimizing information exchange across actors and scales. Appropriate design and tailoring particularly for users who are marginalized because of multiple barriers could potentially level the playing field in access to environmental information and knowledge in support of a polycentric approach to environmental resources management.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2016.10.012.

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